

## HERWIR1.031: New Approach to Parton Shower MC's in Precision QCD Theory

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The new IR-improved Dokshitzer-Gribov-Lipatov-Altarelli-Parisi-Callan-Symanzik (DGLAP-CS) kernels recently developed by one of us is implemented in the HERWIG6.5 environment to generate a new MC, HERWIR1.0(31), for hadron-hadron scattering at high energies. The comparison between the parton shower generated by the standard DGLAP-CS kernels and that generated by the new IR-improved DGLAP-CS kernels is illustrated using MC data. This is done for some of the respective exact  $\mathcal{O}(\alpha_s)$  corrected spectra using the seamless interfaces to MC@NLO while making comparisons with FNAL data. Some discussion of possible implications for LHC phenomenology is also presented.

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Resummed  $\mathcal{O}(\alpha_s^2 L^n)$ ,  $\mathcal{O}(\alpha_s \alpha L^{n'})$ ,  $\mathcal{O}(\alpha^2 L^{n''})$  corrections for  $n = 0, 1, 2$ ,  $n' = 0, 1, 2$ ,  $n'' = 1, 2$ , in the presence of parton showers, on an event-by-event basis, without double counting and with exact phase space are required [1, 2] for precision LHC physics (1% or better total theoretical precision [3]). We present here the first step in realizing our new MC event generator approach to such physics with amplitude-based QED $\otimes$ QCD resummation [4] in the HERWIG6.5 [5] environment by our new parton shower MC for QCD, HERWIRI1.0(31) [6]. HERWIRI1.0(31) already shows improvement in comparison with the FNAL rapidity and soft  $p_T$  data on single  $Z$  production as we quantify below. While the explicit IR cut-offs in the HERWIG6.5 environment will not be removed here, HERWIRI only involves integrable distributions so that these cut-offs could be removed.

We first review our approach to resummation, which can be shown [6, 7] to be equivalent to those in Refs. [8, 9], before we turn to a summary of the attendant new IR-improved DGLAP-CS [10, 11] theory [7] and a description of the implementation of the new IR-improved kernels in the framework of HERWIG6.5 [5] to arrive at HERWIRI1.0(31). We illustrate the effects of the IR-improvement and compare with recent data from FNAL<sup>1</sup>.

In Refs. [4, 7] we have derived the following expression for the hard cross sections in the SM  $SU_{2L} \times U_1 \times SU_3^c$  EW-QCD theory

$$d\hat{\sigma}_{\text{exp}} = e^{\text{SUM}_{\text{IR}}(\text{QCED})} \sum_{n,m=0}^{\infty} \frac{1}{n!m!} \int \frac{d^3 p_2}{p_2^0} \frac{d^3 q_2}{q_2^0} \prod_{j_1=1}^n \frac{d^3 k_{j_1}}{k_{j_1}} \prod_{j_2=1}^m \frac{d^3 k'_{j_2}}{k'_{j_2}} \times \int \frac{d^4 y}{(2\pi)^4} e^{iy \cdot (p_1 + q_1 - p_2 - q_2 - \sum k_{j_1} - \sum k'_{j_2}) + D_{\text{QCED}}} \tilde{\beta}_{n,m}(k_1, \dots, k_n; k'_1, \dots, k'_m), \quad (1)$$

where the new YFS-style [13] residuals  $\tilde{\beta}_{n,m}(k_1, \dots, k_n; k'_1, \dots, k'_m)$  have  $n$  hard gluons and  $m$  hard photons and we illustrate the generic 2f final state with momenta  $p_2, q_2$  specified for definiteness. The infrared functions  $\text{SUM}_{\text{IR}}(\text{QCED})$ ,  $D_{\text{QCED}}$  are defined in Refs. [4, 7]. Eq. (1) is exact to all orders in  $\alpha$  and in  $\alpha_s$ .

The result Eq. (1) allows us to improve [7] in the IR regime the DGLAP-CS [10, 11] kernels as follows, using a standard notation:

$$\begin{aligned} P_{qq}^{\text{exp}}(z) &= C_F F_{\text{YFS}}(\gamma_q) e^{\frac{1}{2}\delta_q} \left[ \frac{1+z^2}{1-z} (1-z)^{\gamma_q} - f_q(\gamma_q) \delta(1-z) \right], \\ P_{Gq}^{\text{exp}}(z) &= C_F F_{\text{YFS}}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+(1-z)^2}{z} z^{\gamma_q}, \\ P_{GG}^{\text{exp}}(z) &= 2C_G F_{\text{YFS}}(\gamma_G) e^{\frac{1}{2}\delta_G} \left\{ \frac{1-z}{z} z^{\gamma_G} + \frac{z}{1-z} (1-z)^{\gamma_G} \right. \\ &\quad \left. + \frac{1}{2} (z^{1+\gamma_G} (1-z) + z(1-z)^{1+\gamma_G}) - f_G(\gamma_G) \delta(1-z) \right\}, \\ P_{qG}^{\text{exp}}(z) &= F_{\text{YFS}}(\gamma_G) e^{\frac{1}{2}\delta_G} \frac{1}{2} \{ z^2 (1-z)^{\gamma_G} + (1-z)^2 z^{\gamma_G} \}, \end{aligned} \quad (2)$$

where the superscript “exp” indicates that the kernel has been resummed as predicted by Eq. (1) when it is restricted to QCD alone and where we refer the reader to Refs. [7] for the detailed

<sup>1</sup>From Ref. [12] the current state-of-the-art theoretical precision tag on single  $Z$  production at the LHC at 14 TeV is  $(4.91 \pm 0.38)\% = (2.45 \pm 0.73)\% (\text{QCD} + \text{EW}) \oplus 4.11\% (\text{PDF}) \oplus 1.10 \pm 0.44\% (\text{QCD Scale})$  and for single  $W^+(W^-)$   $5.05 \pm 0.58\% (5.24 \pm 0\%)$ .

definitions of the respective resummation functions  $F_{YFS}, \gamma_A, \delta_A, f_G, A = q, G$ <sup>2</sup>. See Refs. [4, 7] for discussion of illustrative results and implications of the new kernels and Eq. (1) that are beyond the scope we have here.

We have implemented the new IR-improved kernels in the HERWIG6.5 environment to produce a new MC, HERWIRI1.0, which stands for “high energy radiation with IR improvement”<sup>3</sup>. We modify the kernels in the HERWIG6.5 module HWBRAN and in the attendant related modules<sup>4</sup> with the following substitutions:  $DGLAP-CS P_{AB} \Rightarrow IR-I DGLAP-CS P_{AB}^{exp}$  while leaving the hard processes alone for the moment. We have in progress [16] the inclusion in our framework of YFS synthesized electroweak modules from Refs. [17] for HERWIG6.5, HERWIG++ [18] and MC@NLO [19] hard processes<sup>5</sup>, as the CTEQ [22] and MRST(MSTW) [23] best (after 2007) parton densities do not include the precision electroweak higher order corrections that are needed in a 1% precision tag budget for processes such as single heavy gauge boson production in the LHC environment [2].

The details of the implementation are given in Refs. [4, 6] and we do not reproduce them here due to a lack of space. We have done many comparisons of the properties of the parton showers from HERWIG6.510 and HERWIRI1.031. In general, the IR-improved showers tend to be softer in the energy fraction variable  $z = E/E_{Beam}$  where  $E$  ( $E_{Beam}$ ) is the cms parton (beam) energy for hadron-hadron scattering respectively. See Refs. [4, 6] for the complete discussion of such comparisons. We show in Fig. 1 [6] comparison analyses with the data from FNAL on the  $Z$  rapidity and  $p_T$  spectra as reported in Refs. [24, 25]. We see that HERWIRI1.0(31) and HERWIG6.5 both give a reasonable overall representation of the CDF rapidity data but that HERWIRI1.031 is somewhat closer to the data for small values of  $Y$  (The  $\chi^2/d.o.f$  is 1.77(1.54) for HERWIG6.5 (HERWIRI1.0(31))). Including the NLO contributions to the hard process via MC@NLO/HERWIG6.510 and MC@NLO/HERWIRI1.031 [19]<sup>6</sup> improves the agreement for both HERWIG6.510 and for HERWIRI1.031 (the  $\chi^2/d.o.f$  are changed to 1.40 and 1.42 respectively). That they are both consistent with one another and within 10% of the data in the low  $Y$  region is fully consistent with expectations and is an important cross-check on our work. A more precise discussion at the NNLO level with DGLAP-CS IR-improvement and a more complete discussion of the errors will appear [26]. We also see that HERWIRI1.031 gives a better fit to the D0  $p_T$  data compared to HERWIG6.510 for low  $p_T$ , (for  $p_T < 12.5\text{ GeV}$ , the  $\chi^2/d.o.f$  are  $\sim 2.5$  and  $3.3$  respectively if we add the statistical and systematic errors), showing that the IR-improvement makes a better representation of QCD in the soft regime for a given fixed order in perturbation theory. Adding the  $\mathcal{O}(\alpha_s)$  correction from MC@NLO [19] improves the  $\chi^2/d.o.f$  for the HERWIRI1.031 in both the soft and hard regimes and it improves the HERWIG6.510  $\chi^2/d.o.f$  for  $p_T$  near  $3.75\text{ GeV}$  where the distribution peaks. For  $p_T < 7.5\text{ GeV}$  the  $\chi^2/d.o.f$  for the MC@NLO/HERWIRI1.031 is 1.5 whereas that for MC@NLO/HERWIG6.510 is worse. We await further tests of the new approach, both at FNAL and at LHC. – One of us (B.F.L.W) acknowledges helpful discussions with Prof. Bryan Webber and Prof. M. Seymour and with Prof. S. Frixione. B.F.L. Ward also thanks Prof. L. Alvarez-Gaume and Prof. W. Hollik for the support

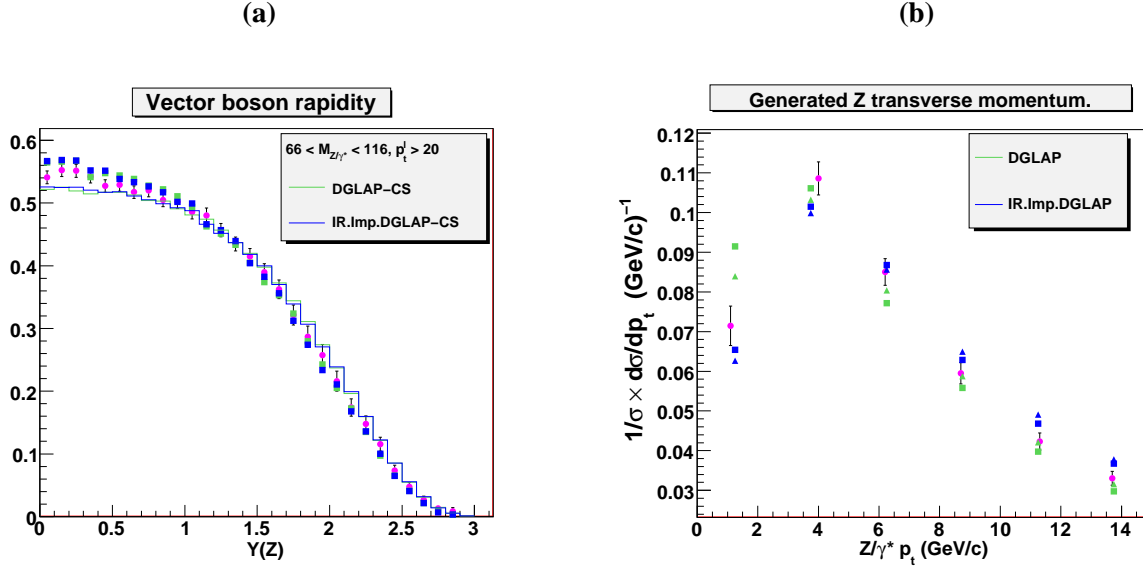
<sup>2</sup>The improvement in Eq. (2) should be distinguished from the resummation in parton density evolution for the “ $z \rightarrow 0$ ” Regge regime – see for example Ref. [14, 15]. This latter improvement must also be taken into account for precision LHC predictions.

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<sup>4</sup>We thank M. Seymour and B. Webber for helpful discussion.

<sup>5</sup>Similar results for PYTHIA [20] and for the new kernel evolution in Ref. [21] are under study.

<sup>6</sup>We thank S. Frixione for helpful discussions with this implementation.



**Figure 1:** Comparison with FNAL data: (a), CDF rapidity data on  $(Z/\gamma^*)$  production to  $e^+e^-$  pairs, the circular dots are the data, the green(blue) lines are HERWIG6.510(HERWIR1.031); (b), D0  $p_T$  spectrum data on  $(Z/\gamma^*)$  production to  $e^+e^-$  pairs, the circular dots are the data, the blue triangles are HERWIR1.031, the green triangles are HERWIG6.510 – in both (a) and (b) the blue squares are MC@NLO/HERWIR1.031, and the green squares are MC@NLO/HERWIG6.510. These are untuned theoretical results.

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